Int J Life Cycle Assess (2012) 17:402–408
DOI 10.1007/s11367-011-0372-9

LCA IN TRANSPORTATION

Life cycle assessment of gasoline in Indonesia

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Received: 22 February 2011 / Accepted: 13 December 2011 / Published online: 18 January 2012

Abstract

Purpose In the Indonesian transportation sector, gasoline is the most consumed fuel; in 2008 it accounted for 60% of the total fuel consumption in transportation. Increasing concern regarding environmental issues, particularly urban air quality, makes the utilization of gasoline in transport a crucial aspect to be analyzed. However, besides tailpipe emissions, there are many upstream processes when producing gasoline which need to be evaluated in terms of impacts to the environment.

Materials and methods Life cycle assessment (LCA) is used as a tool for the assessment of resource consumption and associated impacts generated from utilization of gasoline in the transportation sector including crude oil extraction, oil refining and the use of gasoline in car. The impact categories considered are global warming potential (GWP), acidification potential (AP), eutrophication potential (EP), abiotic resource depletion potential (ADP), human toxicity potential (HTP), and ecotoxicity potential (ETP).

Results and discussion The results show that for global warming, gasoline combustion during end use contributes 93% of the total. The second largest contributor to GWP is oil refining (5%) followed by crude oil extraction (2%). In AP, combustion plays a significant role too with a contribution of 84%, followed by refining with 13% and crude oil extraction with 2%. The most significant process contributing to EP is once again gasoline combustion (95%) and the second contributor is the refining stage (4%), while transport contributes only 1%. For abiotic resource depletion on the other hand, almost 100% of the impact is from crude oil extraction. For HTP, the refining stage plays a very significant role to the life cycle of gasoline contributing 99.6%, whereas for ETP it is refining (62%) and extraction (38%).

Conclusion Using gasoline as transport fuel indicates that gasoline combustion is predominantly responsible for GWP, AP and EP whilst ADP is dominated by crude oil extraction stage and refinery is mainly responsible for human toxicity and ecotoxicity potential,

Perspectives The result of this study can be used as an overview for gasoline production and to compare with other transportation fuel options in Indonesia.

Keywords Gasoline refinery · Indonesia · Life cycle assessment (LCA) · Transportation fuel

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1 Introduction

The Indonesian economy is heavily dependent on oil. In 2008, 45% of the final energy consumption was contributed by oil products (MEMR 2009). For oil-based fuels consumption itself, 61% is attributed to the transportation sector (MEMR 2009), and it is forecasted to increase in the years ahead. Data from 1990 to 2008 show that oil fuel consumption in the transportation sector increased 5.2% annually on average (Fig. 1).

Gasoline is the most consumed fuel in the Indonesian transportation sector; in 2008 it accounted for 60% of

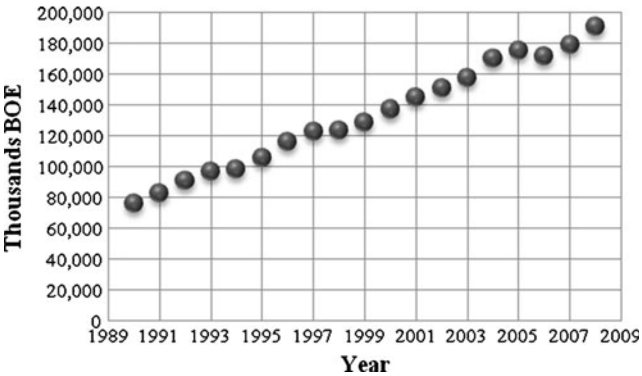

Fig. 1 Oil fuel consumption in Indonesia's transport sector (MEMR 2005, 2009)

the total fuel consumption in transportation. Increasing concerns regarding environmental issues, particularly urban air quality, makes the utilization of gasoline in transport a crucial aspect to be analyzed. However, besides tailpipe emissions, there are many upstream processes when producing gasoline which need to be evaluated in terms of impacts to the environment. The upstream processes such as crude oil extraction and refining as well as distribution also contribute to environmental impacts. It is therefore necessary to assess thoroughly the environmental impacts from gasoline as well as to identify the environmental hotspots throughout the entire life cycle of gasoline from "cradle to grave" or as it is sometimes referred, "well to wheels".

This study attempts to provide an assessment of environmental impacts for gasoline production and utilization in Indonesia according to the life cycle assessment (LCA) perspective. The results of this study can be used to compare with other transportation fuel options in Indonesia.

2 Materials and methods

2.1 Goal and scope

The aim of this study is to assess the environmental impacts of gasoline during the fuel production through utilization processes. Climate change is a worldwide concern and of

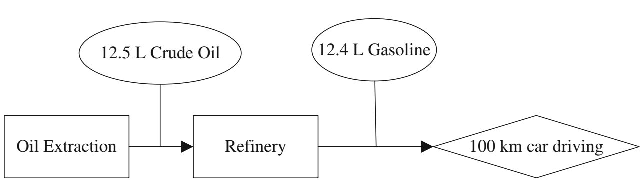

Fig. 2 Mass flow of 100 km traveling with gasoline fueled Toyota Kijang LSX 1800 cc

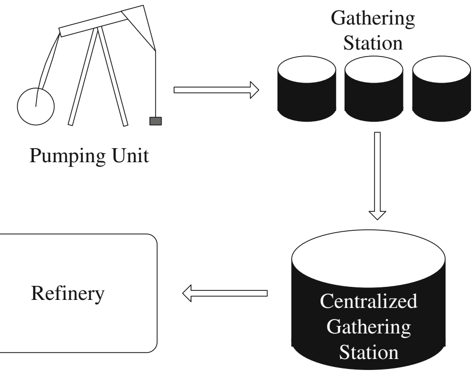

Fig. 3 Flow diagram of oil extraction

particular significance to Indonesia which is an archipelagic nation and susceptible to rises in sea levels; hence global warming is one of the environmental impact categories of interest. Moreover, despite adequate rainfall over most in Indonesia with average values between 2,000 and 3,000 mm/year, some islands like Java face water shortages particularly in relative dry year (Goltenboth et al. 2006). In particular, two phenomena—eutrophication and acidification—are of great concern in relation to the ecology of lakes; therefore, both impacts will be chosen as the environmental impact category of interest as well. Furthermore, as crude oil is a non-renewable resource, it is also important to consider abiotic resource depletion in this study. As emissions during the refining and combustion of gasoline can have significant impacts on toxicity, human and ecological toxicity potentials are also included in the study.

The data obtained for the study are mainly from primary sources such as energy, raw materials, chemicals, from plant records. On the other hand, existing literature data is also used for emissions from energy conversion and transportation; e.g., Ecoinvent, IPCC, USEPA, databases in the Simapro software and other sources are used in the absence of primary data.

2.2 System boundaries

The system boundary includes extraction of crude oil in the ground, crude oil refining process to produce gasoline, the

Table 1 Indonesian electricity mix by fuel type (2007)

Generation type	Share (%)	Amount (TW h)
Coal	41	52.89
Natural gas	14	18.06
Geothermal	3	3.87
Hydro	9	11.61
Oil	33	42.57
Total	100	129

Table 2 Life cycle inventory for extracting 1 kl crude oil

Item	Amount	Unit
Raw material in the ground		
Crude oil	7.85E−06	Barrel
Natural gas	7.61E−05	SCF
Salty water	1.78E−01	kL
Energy		
Diesel (pump)	1.12E−10	kL
Electricity	5.35E−01	kWh
Waste		
Flared NG	4.57E−06	SCF
Waste water	1.79E+02	L
Products		
Crude oil transported	9.98E−01	kL
Natural gas	6.68E−05	SCF
Transportation		
Diesel (pump)	5.89E+00	MJ
Air emissions	Total	
CO_2	5.70E+04	g
SO_2	1.44E+02	g
NO_x	8.6E+01	g
CO	1.18E+01	g
CH_4	5.77E+01	g
N_2O	4.37E−01	g
Water emissions		
Arsenic	3.56E−03	g
Benzene	8.37E−02	g
Boron	1.76E+00	g
Sodium	1.67E+03	g

use of gasoline, as well as all transportation between those processes.

2.3 Functional unit

The functional unit used in this study is driving 100 km in passenger car (Toyota Kijang LSX 1800 cc). The mass flow is shown in Fig. 2.

3 Life cycle inventory

3.1 Oil extraction

Data for this phase were collected from one of the big oil companies in South Sumatra. Onshore oil extraction is the common practice there. The flow diagram for oil extraction is shown in Fig. 3.

About 90 oil wells at the site use pumping units for extracting the crude oil, 70 wells getting crude oil by artificial gas lift such as electrical submersible pumps (ESP) and gas lift, and about 50 wells by natural lift process. Besides using artificial lift, they also apply waterflooding technology to increase the production in some wells. In this study, pumping units are considered for extracting the crude oil from the ground. The products from the extraction process are 80% saltwater and 20% oil and gas. As Fig. 3 shows, the products of oil well are sent to gathering stations around the city from where they are delivered to a centralized gathering system. In the centralized gathering system, products are separated into three types, namely crude oil, natural gas and saltwater. The crude oil is transported from the centralized gathering station to the refinery about 90 km away by pumping via a trunk line. Diesel is used for this pump; emissions from diesel combustion are from Ecoinvent (Jungbluth 2007a).

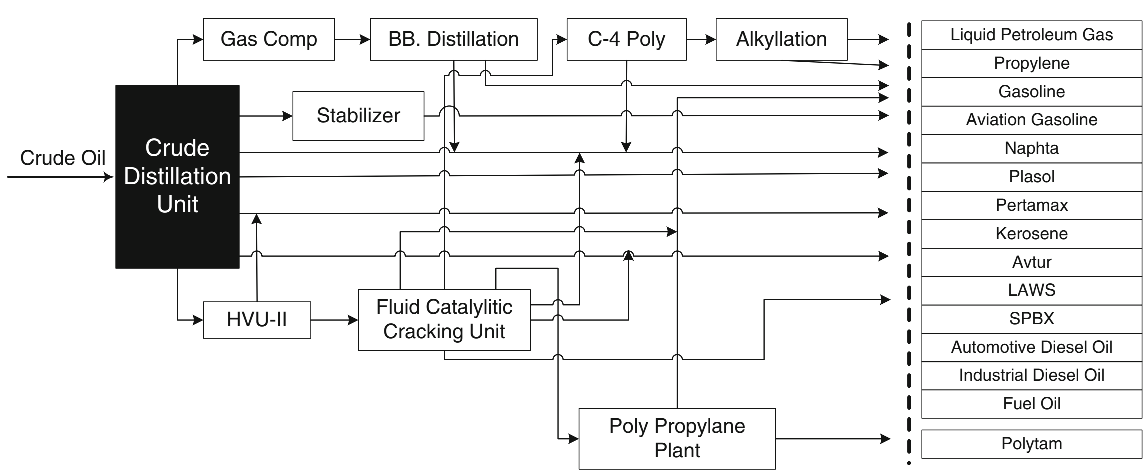

Fig. 4 Process flow diagram of the refinery

The fraction of natural gas and crude oil are averaged from the production in all the wells in the city.

Crude oil produced in the city=518,893 barrel
Natural gas produced in the city=5,518,470 ft^3
Since crude oil produced at exploration plant is 12,000 barrels,
Then, natural gas produced=127,621 ft^3

As both co-products are energy carriers, to make a fair comparison allocation has been made based on energy. Since 1 barrel of crude oil is equivalent to 5,487 standard cubic feet (SCF) of natural gas, allocation to the crude oil is 99.83%. This allocation factor was used for the emissions from extraction as well. Emissions from the flaring of natural gas are from Ecoinvent (Emmenegger 2007b)

GHG emission factor for electricity was taken from the Indonesian average grid mix (State Electricity Company 2009), while the other emissions from electricity production for each type of fuel of power plant were calculated based on databases in Ecoinvent (Bolliger 2007; Emmenegger 2007a; Jungbluth 2007b; Roder 2007) using the grid mix from (Mochtar 2008); details of which are presented in Table 1.

The life cycle inventory for extracting 1 kl crude oil is presented in Table 2.

3.2 Refinery

Data were collected from a large refinery in Plaju, South Sumatra based on annual records from the year 2009. The specific units in this refinery are Crude Distillation Unit (CDU), Fluid Catalytic Cracking Unit (FCCU), Polypropylene (PP) Plant, Alkylation, and Polymerization. The process flow diagram of the refinery is shown in Fig. 4. The refinery products comprise of: gasoline (17.63%), kerosene (8.69%), Automotive Diesel Oil (ADO) (22.89%), Industrial Diesel Oil (IDO) (0.88%), and Fuel oil (IFO) (11.78%) and others listed in Table 3.

As there are many co-products at this stage, allocation of environmental burdens is a critical issue. According to ISO 14044:2006 (ISO 2006), allocation should be avoided if possible by dividing the unit process or expanding the product system. Both these approaches are not possible to apply. Hence, the next step in the hierarchy, allocation based on physical relationship between inputs and outputs is considered. Mass and energy based allocation seem to be possible considerations. As seen in another similar study, energy and mass-based allocation yield similar results (Wang et al. 2004). Hence, a mass based approach was used as only mass data was available for some of the co-products shown in Fig. 4 and Table 3. The fuel products (gasoline, jet fuel, LPG) are sold to the southern region of Sumatra whereas the special fuels such as avigas, polytam, solvent, musicool, HAP are sold on the national market. Naphtha and fuel oil are exported. Energy used in the refinery is from fuel oil, refinery gas and mix gas, data of which are from plant records. Secondary data were used in this study for estimating the emissions from flue gas from catalyst regeneration in refinery units (USEPA 1995), emissions from fuel oil combustion from Ecoinvent (Jungbluth 2007c), gas flaring (Jungbluth 2007d), and refinery gas from Ecoinvent (Jungbluth 2007e). Wastewater constituents and concentrations were calculated according to Lenntech (2010).

Table 3 Life Cycle Inventory for refining 1 kL gasoline

Item	Amount	Unit
Crude oil	1.01E+00	kL
Energy		
Fuel oil	3.46E−03	Ton
Refinery gas	4.83E−03	Ton
Mix gas	3.59E−02	Ton
Product		
Gasoline	1.00E+00	kL
Co-products		
Kerosene	4.93E−01	kL
ADO (Automotive Diesel Oil)	1.30E+00	kL
Avtur (Aviation Turbine Fuel)	1.10E−01	kL
IDO (Industrial Diesel Oil)	5.01E−02	kL
IFO (Intermediate Fuel Oil)	6.68E−01	kL
Avigas (Aviation Gasoline)	0.00E+00	kL
Pertamax (Unleaded gasoline with RON 92)	1.03E−02	kL
LPG	1.98E−01	kL
SPBX (Special Boiling Point X)	2.00E−02	kL
LAWS (Low Aromatic White Spirits)	1.06E−02	kL
Musicool (Hydrocarbon Refrigerant) and HAP (Hydrocarbon Aerosol Propellant)	9.18E−04	kL
Polytam (polypropylene)	7.30E−02	kL
Naphtha (excess)	1.09E+00	kL
Vacuum residue	6.30E−01	kL
Long residue	0.00E+00	kL
POD (Mix. vacuum gas oil)	2.13E−02	kL
Air emissions		
SO_2	6.54E+02	g
NO_x	3.55E+02	g
CO	4.77E+03	g
CO_2	1.53E+05	g
CH_4	2.49E+01	g
1,1,1-Trichloroethane	5.26E−10	g
Fluorene	5.00E−06	g
N_2O	8.97E−02	g
NO_2	2.44E+01	g
NH_3	1.85E+01	g
Water emission		
BOD	6.88E+02	g
COD	1.55E+03	g

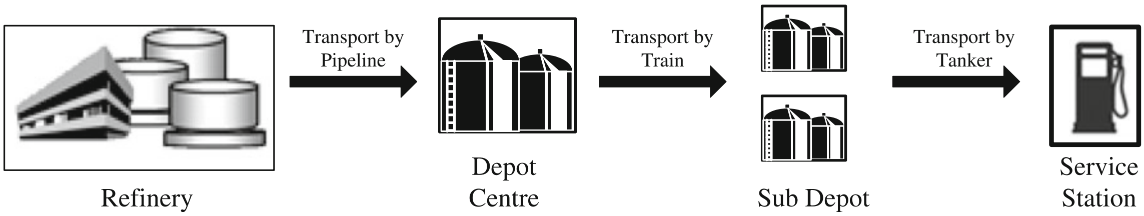

Fig. 5 Gasoline distribution system

Pipeline is used to transfer gasoline to the storage tank, in south of Sumatra, whilst barge with 500- to 1,800-ton capacity is used to transfer gasoline to farther locations. The distribution system of gasoline in this study is illustrated in Fig. 5. Emission factors for pipeline transport were derived from IPCC (Picard 2001) and rail transport from US LCI (Franklin Associates 2008).

Emissions from refinery are in the form of liquid waste, gas, and solid waste.

- Liquid waste

Sources of liquid waste are water from the production process, storage tank, utilities, laboratory, rain and residential waste. Liquid waste is treated with oil catcher/separator for trapping the oil in the sewer and then transferring it to the Redistilling Unit, while clean water flows into the Musi River. The liquid emissions discharged to the river are considered non hazardous waste going to the environment. There are eight units of oil catcher: five API Gravity type and three CPI (Corrugated Plate Interceptor) type.

- Gas

Most of emissions to air are ethane and methane gas which are emitted from the top column distillation and fractionation unit in the refinery. The gases are burnt in three flaring units. Emissions from these flaring units are included in the data inventory.

- Solid Waste

Solid wastes originate from the Polypropylene unit only during emergency/shutdown from the cleaning tank. This solid waste is treated by incineration (incinerator capacity 710 kg/day). Since it was assumed that process refinery runs in standard condition without emergency, solid waste was not considered.

3.3 Combustion

The vehicle considered for the use phase in this study is a minibus Toyota Kijang LSX having 1,800 cm^3 capacity with Electronic Fuel Injection (EFI) technology. It consumes 12.4 l of gasoline for traveling 100 km using Urban Driving Cycle (780 s) plus Extra Urban Driving Cycle (420 s). Data related to the emissions from gasoline combustion were taken from vehicle emission testing in Bandung, Indonesia from (Lestari 2005; Nur et al. 2010) for CO_2 and CH_4 and from (Lestari 2005) for CO, HC and NO_x.

Life cycle inventory of tailpipe emissions from 1 l gasoline use is presented in Table 4.

4 Results and discussion

Impact assessment was conducted based on the CML 2000 method. The results of the six environmental impact categories considered in the study are summarized in Table 5, while the percentage rates are described by the graph in Fig. 6. The detailed information about each impact in this study is explained in the following subsections.

4.1 Global warming potential (GWP)

Table 5 shows that the total GWP is 3.61E+04 g CO_2-eq. It means that driving 100 km will give 36 kg CO_2-eq burden to the environment. Gasoline combustion during end use is responsible for 93% of the GWP (see Fig. 6), mainly due to CO_2 emissions. The second largest contributor to GWP is oil refining (5%) followed by crude oil extraction (2%). At the refinery, energy contributes 73% due to the high amount of CO_2 emission from refinery gas combustion, and flaring 24%. The remaining GWP is contributed by diesel powered rail and diesel combustion in pump during the transportation.

Table 4 Life cycle inventory of air emissions for combusting 1 l of gasoline

Item	Amount	Unit
CH_4	3.14E−01	g
CO	3.90E+02	g
HC	6.11E+01	g
NO_x	8.51E−00	g
CO_2	2.69E+03	g

Table 5 The impact potential contributions of various life cycle stages of gasoline (per 100 km driving)

Potential	Stage				Total
	Crude oil extraction	Refinery	Gasoline combustion	Transport	
GWP (g CO_2-eq)	7.24E+02	1.85E+03	3.35E+04	5.98E+01	3.61E+04
AP (g SO_2-eq)	1.80E+00	1.09E+01	7.41E+01	1.17E+00	8.79E+01
EP (g PO_4-eq)	0.00E+00	4.92E−01	1.38E+01	2.13E−01	1.45E+01
ADP (g Sb-eq)	2.65E−01	1.84E−13	0.00E+00	0.00E+00	2.65E−01
HTP (g 1,4 DCB-eq)	1.78E+04	4.05E+06	0.00E+00	1.15E+02	4.07E+06
ETP (g 1,4 DCB-eq)	1.16E−01	1.87E−01	0.00E+00	0.00E+00	3.03E−01

4.2 Acidification potential (AP)

The AP is contributed by SO_2, NO_x, SO_3, NO_2 and NH_3 emissions, with the total being 87.9 g SO_2-eq. As for the case of GWP, for AP too, combustion plays a significant role with a contribution of 84%. The next contributor is refining with 13% followed by crude oil extraction with 2%. The whole contribution from combustion is attributed to NO_x emitted from car tailpipe. At the refinery, flaring contributes 60%, the remaining coming from FCCU, transport and the use of energy. At the crude oil extraction stage, electricity contributes 97% of the acidifying emissions, the remaining being contributed by transportation.

4.3 Eutrophication potential (EP)

The total EP in this research as described in Table 5 is 14.5 g PO_4-eq. Pollutant contributors to EP are NO_x, NO_2, NH_3 and COD. The most significant process contributing to EP is gasoline combustion (95%) and the second contributor is the refinery stage (4%), while transport contributes 1%. The only one significant pollutant contributing to EP is NO_x from gasoline combustion. In the refinery, the dominant contribution of eutrophication is by COD emission from wastewater (38%), followed by flaring and transport at 18% each and fuel combustion 15%.

4.4 Abiotic depletion potential (ADP)

The amount of ADP per functional unit is 0.249 g Sb-eq. As expected, almost 100% of the abiotic resource depletion is from crude oil extraction, due to the crude oil being extracted from nature. Other substances contributing to ADP, such as arsenic, boron, sodium and fluorine are only in very small amounts and therefore not significant.

4.5 Human toxicity potential (HTP)

Total HTP per functional unit is 4.07E+06 g 1,4 DCB-eq (see Table 5). For human toxicity, refinery plays a very significant role to life cycle of gasoline accounting for 99.6%. This is due to the benzene from wastewater in the refinery.

4.6 Ecotoxicity potential (ETP)

Total ETP (in terms of freshwater aquatic ecotoxicity) is 0.308 g 1,4 DCB-eq. The emissions which contribute are mainly arsenic and benzene with smaller contributions from ethylbenzene, formaldehyde, naphthalene, 1,1,1-trichloroethane, toluene, anthracene, etc. The refinery stage generates a large amount of pollutants contributing 62%, like HTP also due to the benzene in the wastewater. On the other hand, crude

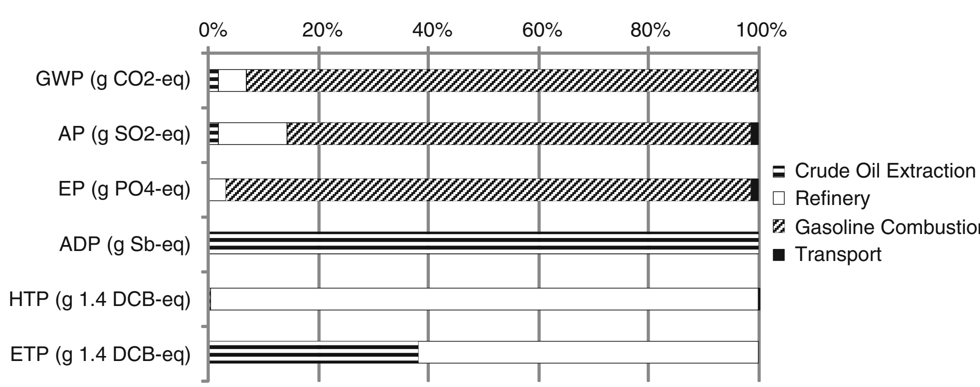

Fig. 6 Contribution of the gasoline life cycle stages to the various impact potentials

oil extraction contributes 38% of ETP due to the arsenic in the wastewater.

To put the results of this study into perspective, they were compared a similar study by (Nguyen and Gheewala 2008). The results of this research for GWP were only about 3% lower than those from the other study. However, in term of AP, in this research give a significantly higher result (115%). A comparison of the inventory results show that the SO_2 emissions from the refinery for both the studies are quite similar as expected. However, the difference arises mainly due to the NO_x emissions from the combustion of gasoline in vehicles probably due to different vehicles being considered in the two cases and different driving cycles; this study uses the Bandung driving cycle, whereas Nguyen and Gheewala (2008) use the Bangkok driving cycle.

5 Conclusions

In this study, the LCA method is used to assess the environmental impacts of gasoline production and utilization in Indonesia. The results of this LCA study of using gasoline as transport fuels indicate that driving 100 km in a passenger car using gasoline has a potential to contribute GWP, AP, EP, ADP, HTP, and ETP at 36.1 kg CO_2-eq, 87.9 g SO_2-eq, 14.5 g PO_4^{3-}-eq, 0.265 g Sb-eq, 4,070 kg 1,4 DCB-eq and 0.308 1,4 DCB-eq, respectively. Gasoline combustion is dominantly responsible for GWP, AP and EP, whilst abiotic depletion is dominated by crude oil extraction and the dominant contributor for human toxicity potential and ecotoxicity potential is the refinery stage. This study can provide a base case for comparison for future assessments of alternative fuels that the Government of Indonesia may propose to use for reducing the dependence on oil. Other alternative fuels which result in a better environmental performance compared to gasoline could be considered to be options to diversify energy mix in Indonesia.

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